Fermilab Main Injector Abort Kicker System

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The Fermilab Main Injector will require an updated abort kicker system. A new modulator and modified magnet are required to meet the new requirements. Two Main Ring abort magnets will be modified to contain a 12.5 Ω load resistor in series with the existing magnet. A pulse transformer is used with a 3.1 Ω, 10 µs pulse forming network to reduce the capacitor voltage to 34 kV and allow operation in air. The pulse transformer primary is floated to allow grounded cathode operation of the thyratron and a grounded terminal on the pulse forming network capacitors.

I. INTRODUCTION

The Fermilab Main Injector is a new 150 GeV synchrotron now under construction. The Main Injector has been designed to replace the existing Main Ring but with an increased aperture. This increase, along with other accelerator upgrades, has been designed to support a luminosity in excess of $5\ 10^{31}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ in the Tevatron. While some components will be moved from the old Main Ring to the new Main Injector, the abort kicker modulator must be redesigned and the abort kicker magnet must be modified.

Siting constraints have forced the abort kicker modulator to be located ~100 m from the kicker magnet itself, much further than the existing distance of ~12 m in the Main Ring and ~40 m in the Tevatron. At the same time, the rise time of the field has been decreased from 1.8 µs in the Main Ring to 1 µs in the Main Injector. To meet specifications, a pulse forming network is required in place of the circuit used in the Main Ring [1] and Tevatron.

II. DESIGN TOPOLOGY

The circuit currently used for the Main Ring abort kicker is shown in simplified form in Fig. 1. That this circuit can not be used follows from the explanation of its operation. The initially charged capacitor, C, is switched through S to the cable, TLINE, and the inductance of the abort magnet, LMAG. If a simple lumped circuit model is used for the cable, the energy is resonantly transferred from the capacitor to the inductance of the magnet and cable. When the capacitor voltage begins to reverse, the current is allowed to free wheel through the anti-parallel diode, D, across this inductance. The result is a quarter sine rise and a long exponential tail due to diode forward drop and magnet and cable resistance. This is the fundamental operation of the circuit if the magnet current rise time is much less than the cable transit time, since then the cable may be treated as lumped inductance and capacitance. But if the magnet current rise time is much greater than the cable transit time, a RC snubber should be added at the magnet. The circuit operates then as a low impedance source connected through a transmission line to a high impedance load. The cable RC termination reduces the reflections from the magnet and the effect of those reflections on the rise time.

The magnet is always initially driven by the characteristic impedance of the cable during the cable round trip transit time. For the Main Ring abort kicker, which has a required field rise time of 1.8 µs, the cable round trip transit time is 120 ns. The magnet voltage has several steps on it as the current builds up over several cable transit times. Conversely, the Main Injector abort kicker has both a required field rise time and a cable round trip transit time of 1 µs. If this magnet has a RC snubber, then almost as much energy will be used charging the RC snubber as charging the magnet. But, if the magnet has no snubber, neither the rise time nor the flat top specifications can be met. There are two circuits that can be used to meet specifications.

Both circuits require a source that is impedance matched to the transmission line. Therefore, a constant impedance pulse forming network (PFN) must be used to drive a cable with the same impedance. In one method, the magnet is terminated with a series resistance equal to the source impedance. In the other method, no magnet termination is used, but a matched impedance back termination is required at the PFN. All the pulse energy will go into the termination resistor, whether located at the magnet or at the end of the PFN. There are several tradeoffs for each method.

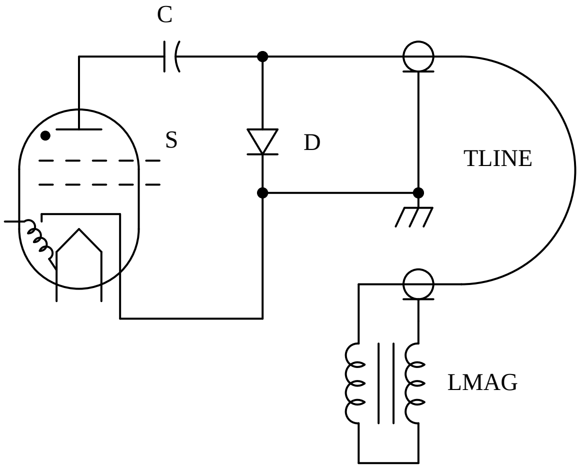

Figure 1

Typical Fermilab Abort Kicker Magnet System

Table I, Main Injector Abort Kicker Specifications

Field rise time (10 % – 70 %) (10 % – 90 %)	700 ns 1 µs
Field flat top	>9.8 µs
Field flatness (ΔB/B)	± 10%
Field fall time	NA
$\int$B dl (Total kick/ 2 Magnets)	0.37 kG m (8 GeV) to 2.51 kG m (150 GeV)
Repetition Rate	0.4 – 0.7 Hz
Magnet Inductance	5.05 µH
Magnet Current	2700 A
Magnetic Gap	50.8 mm
Magnetic Length	1.89 m

For the back termination case, no cooling is required in the tunnel at the magnet. However, active cooling is required in the modulator cabinet to dissipate the 750 W of power. The back termination diode also conducts full current on each pulse. With the magnet termination case, cooling is now needed in the tunnel. While this is one more component actually in the tunnel enclosure, there is an ample supply of low conductivity water for cooling magnets in the tunnel. The series resistance termination at the magnet was therefore chosen for this application.

A source and load impedance of 6.25 Ω would be required to safely meet the specifications in Table I given the magnet inductance. Given the source impedance and the maximum peak current, 120 % of nominal, the PFN charge voltage is 2 I_{pk} Z_0, ~ 40 kV. A PFN and switch can be made to operate with these parameters, however there is concern regarding the voltage across the magnet. There is currently an occasional breakdown problem in the Main Ring and Tevatron kicker magnets when operating at a peak voltage of 35 kV.

For a pulse forming network with a "fast" rise time, the magnet will have almost 100% overshoot, 40 kV, across it during the field rise time because it presents an open circuit to the leading edge of the pulse. The typical kicker magnet is made of many LC sections and the voltage overshoots very little as long as the rise time from the PFN is comparable to the rise time for one section of the magnet. This abort kicker magnet is simply a lumped L, so a PFN rise time not fast compared to $\tau_{mag} \equiv L/(2\ R)$ [magnet inductance / (2 x source impedance)] is required to keep the overshoot small.

This last requirement changes the current rise time to the convolution of the input voltage with the magnet operational impedance. Assuming an exponential rising magnet voltage with time constant τ_V and assuming $\tau_V = \tau_{mag}$, the magnet time constant, the 10 % – 90 % current rise time will be approximately 3.45 τ_{mag}. While a 10 Ω system would nominally meet specifications, there would be little room left for jitter and variable delay in thyratron conduction with voltage. Therefore, a 12.5 Ω impedance is required. This then impacts back upon the magnet voltage. With a 12.5 Ω impedance, a 80 kV PFN charge voltage is required.

There is however some further gain that can be made by lowering the PFN charge voltage. The possibility of operating the PFN in air results in a much more maintainable modulator than one submersed in oil. The modulator can also be cheaper if the cost of a pulse transformer is less than the cost of the oil enclosure. That is the case for this modulator and a 1:2 step up transformer was chosen. This step up transformer maintains the peak voltage at the magnet to ~ 30 kV and reduces the PFN charge voltage to ~ 40 kV. In addition, the pulse transformer primary is floated at the PFN charge potential. This makes the thyratron auxiliary circuits much easier.

A simplified schematic of the new abort kicker power supply is shown in Figure 2.

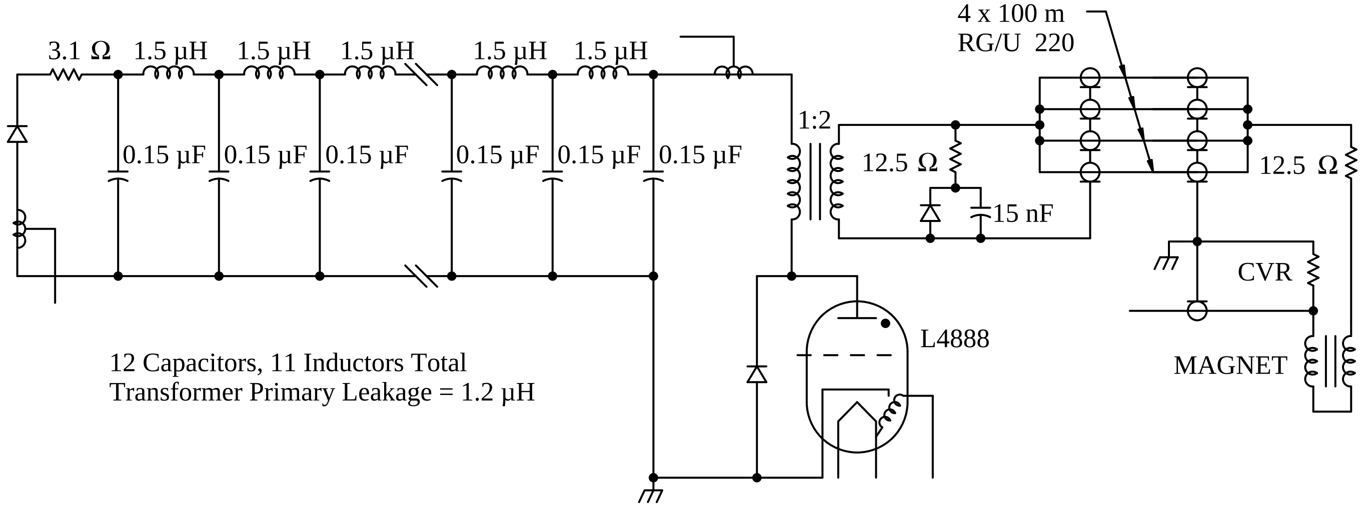

Figure 2

Main Injector Abort Kicker Schematic

III. EXPERIMENTAL RESULTS

There has been only one serious problem to date with the system. It was originally hoped that the system would fit into one 19" relay rack. There have been partial discharge problems with this configuration, especially near the transformer primary connections to the thyratron. The system has only been able to operate up to 85 %, 30 kV, of the nominal voltage. The system has been rearranged to fit into three 24" shielded relay racks. A new cabinet to house the modulator has been ordered and operation at 120% of nominal voltage should be achieved then.

The magnet current and voltage waveforms are shown in Fig. 3 for operation at 75% of nominal. Minimal tuning was performed to obtain these waveforms. The measured performance of the system is shown in Table II and meets or is better than specifications. While the raw rise time specification has been easily met, at least an additional 100 ns will be needed to account for jitter and the change in thyratron conduction delay with the wide range in operating voltage, from 4 kV to 40 kV. Delay and jitter will be minimal at the nominal voltage, and therefore the decrease in rise time over specification should reduce activation in the magnets downstream from the abort kicker.

The magnet voltage has also been kept to a minimum. At maximum operating voltage, 120 %, the magnet voltage will be below 30 kV, still below the current operating voltage of 35 kV. This should ensure reliable operation of the magnets for their new duty in the Main Injector.

Table II, Main Injector Abort Kicker Measured Performance

Field rise time (10-70%) (10-90%)	450 ± 20 ns 720 ± 20 ns
Field flat top	10.4 µs
Field flatness (ΔB/B)	± 5%

IV. CONCLUSIONS

The Main Injector required an updated abort kicker system. This system has been operational at 85% voltage for several months now and to date has met performance specifications. Full voltage operation will happen within the next year and the system will be burned in for approximately a year before installation and commissioning in the Main Injector are required.

V. REFERENCES AND ACKNOWLEDGMENTS

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[1] Abort Kicker Power Supply Systems at Fermilab, G. Krafczyk, G. Dugan, M. Harrison, K. Koepke, E. Tilles, IEEE Trans. Nuc. Sci., Vol. NS-32, No. 5, October 1985, pp. 3581-3583

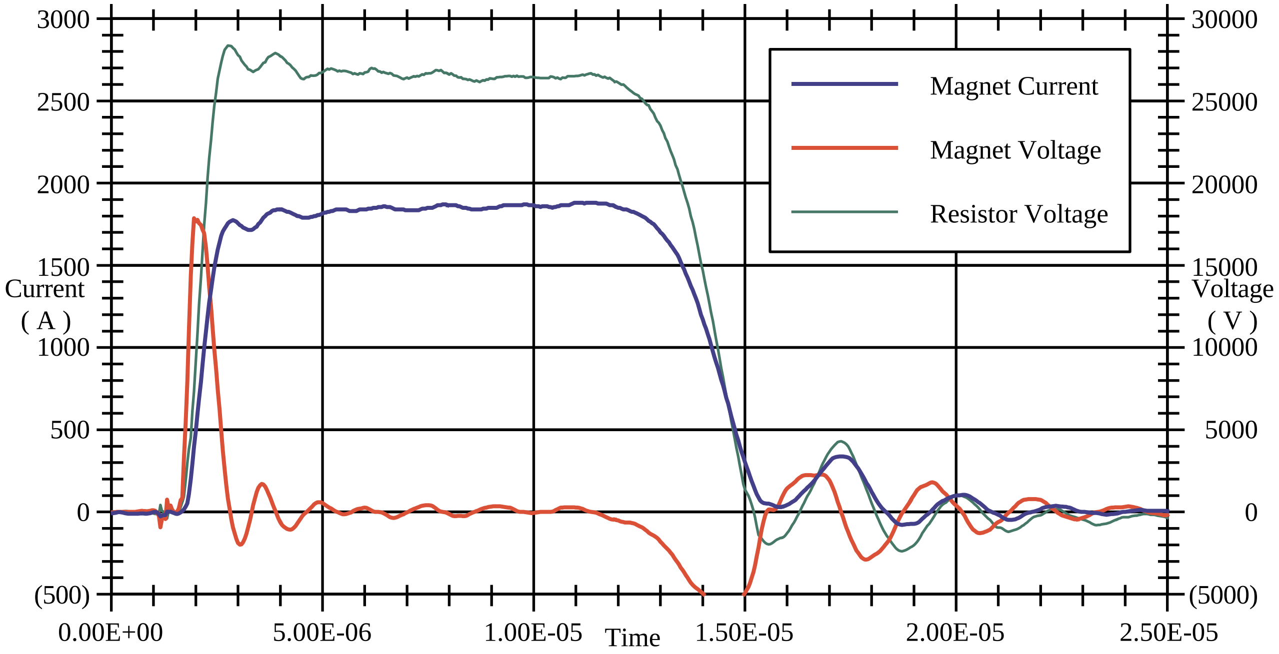

Figure 3

Measured Magnet Current at 75% Operating Level